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Gas Evolution in Protoplanetary Disks

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Abstract. This article summarizes a Splinter Session at the Cool Stars XV conference in St. Andrews with 3 review and 4 contributed talks. The speakers have discussed various approaches to understand the structure and evolution of the gas component in protoplanetary disks. These ranged from observational spectroscopy in the UV, infrared and millimeter, through to chemical and hydrodynamical models. The focus was on disks around low-mass stars, ranging from classical T Tauri stars to transitional disks and debris disks. Emphasis was put on water and organic molecules, the relation to planet formation, and the formation of holes and gaps in the inner regions.

Keywords: Solar system: origin and evolution, Accretion and accretion disks; Mass loss and stellar winds; Protostars; Infrared excess, debris disks, protoplanetary disk; Atomic, molecular, chemical, and grain processes
PACS: 96.12, 97.10.Gz, 97.10.Me, 97.21, 97.82, 98.38.Bn

INTRODUCTION

Most of the current knowledge about the structure and evolution of protoplanetary disks (photometry, SED class, images in scattered light, etc.) originate from the dust component, whereas the gas in protoplanetary disks is, in many cases, more difficult to observe and more difficult to model (see Fig. 1). Yet, it is the gas component that contains 99% of the disk mass and sets the initial conditions for planet formation. The gas is responsible for the delivery of water and organic material to terrestrial planets and, by its dispersal, drives the evolution to debris disks.

With existing and new telescopes (SPITZER, HERSCHEL, SOFIA, JWST, ALMA), tracers of the gas in form of emission lines of atoms, ions and molecules can be observed. These observations allow for a direct determination of the gas mass, the temperature distribution and the chemical composition of the gas independent of the dust, provided that we can trust the models. By comparing objects of different ages, the evolution of the gas in protoplanetary disks can be revealed.

Since UV, infrared, and millimeter lines probe very different regions in the disks, observations generally need to be combined to obtain a complete and consistent picture

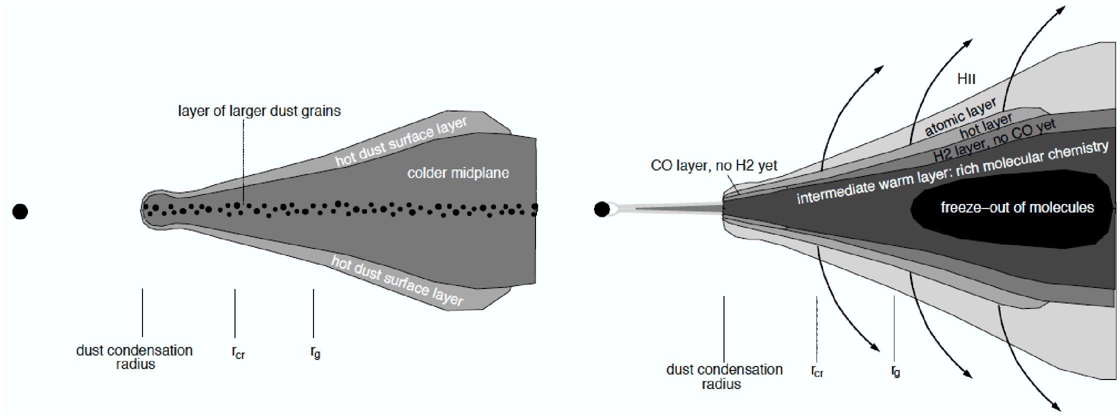

FIGURE 1. Comparison of the structure of a flaring protoplanetary disk in dust (left) and gas (right). From Dullemond et al. (2007).

of the physical and chemical state of the gas in protoplanetary disks. Here, models play an essential role to convert observations into understanding. Given these new challenges, astronomers and theoreticians around the world have started to "hunt" the gas in protoplanetary disks. Key questions are:

- How does the gas-to-dust ratio vary with age, starting from the initial interstellar value of 100:1 to virtually 0:1 in debris disks?
- What is the density structure, temperature, and dynamics of the gas in protoplanetary disks at different ages?
- What is the chemical composition of the gas in the regions where terrestrial and where gas giant planets form?
- What is the driving mechanism for the gas mass loss? How does the dust component react on the gas removal?
- Does the gas removal truncate the process of planet formation?

TALK SUMMARIES

1. Current and Future Observations of Gas Disks

Jonathan Williams reviewed the observational methods from the UV to millimeter, outlining how spectral profiles can be used to derive gas properties. Starting from the inner disk, at radii up to a few AU, near-IR transitions such as the fundamental CO lines around 4.7 μm can probe the regime of terrestrial planets, and are readily detectable in Classical T Tauri stars. They have been used to show that gas is present *within* the co-rotation and dust-emitting radii (Carr 2007, Pontoppidan et al. 2008).

Spitzer mid-infrared spectroscopy has probed gas further out in the terrestrial zone. The results have set limits on H_2 (e. g. Pascucci et al. 2007), have shown strong [Ne II] emission from X-ray ionization of the disk surface (e. g. Lahuis et al. 2007), and detected disks full of water and organic molecules (Watson et al. 2007, Salyk et al. 2008).

Millimeter lines probe the cold outer reservoir, and CO rotational lines are detected in $\sim$100 disks. However, photo-dissociation and freeze-out on grains can greatly affect the gas abundances, which makes mass estimates uncertain. CO is rarely detectable around the older debris disks (e. g. Dent et al. 2005) and the results suggest that the gas dissipates from the inside out (e. g. Hughes et al. 2008). One key observation in these disks is the D/H ratio. This is an important method of constraining the origin of water on Earth, and the first observational measurements of the D/H profile across a disk have recently been made by Qi et al. (2008).

In the future, observations of gas in disks will be greatly advanced by the spectroscopic capabilities of upcoming missions. In 2009, the 3m-class telescopes SOFIA and HERSCHEL will open up the far-infrared wavelength range, looking at gas and dust in the giant planet formation regions. By 2012, ALMA will provide orders of magnitude improvement in resolution and sensitivity in the sub-mm, diagnosing gas in the cold disk, and potentially directly imaging giant proto-planets. In 2013, JWST will provide similar improvements in the near and mid-IR. Later in this decade, telescopes such as TMT and ELT will allow diagnosis of gas and dust in the terrestrial planet forming zone.

By combining data from these new missions with models of the disks, we hope to understand the gas dissipation and evolution, the structure, dynamics and chemistry, and the effect and signatures of protoplanets within these disks. But in addition, we can expect such new facilities to turn up the unexpected.

2. Accretion in Evolved and Transitional Protoplanetary Disks

Aurora Sicilia-Aguilar summarized how the accretion process can be analyzed by U-band photometry and Hα spectroscopy, helping to understand the mechanisms involved in the disk dissipation and in the formation of inner gaps. The U-band excess method is often preferable for K-M stars and has less systematic uncertainties as compared to Hα, but it is also limited to about $\dot{M} > 10^{-10}\,M_\odot/yr$ (Sicilia-Aguilar et al. 2006b). Comparing the results for intermediate-aged young clusters, the median accretion rate in the 4-Myr-old cluster Tr 37 is $\dot{M} \sim 10^{-9}\,M_\odot/yr$, which is about one order of magnitude

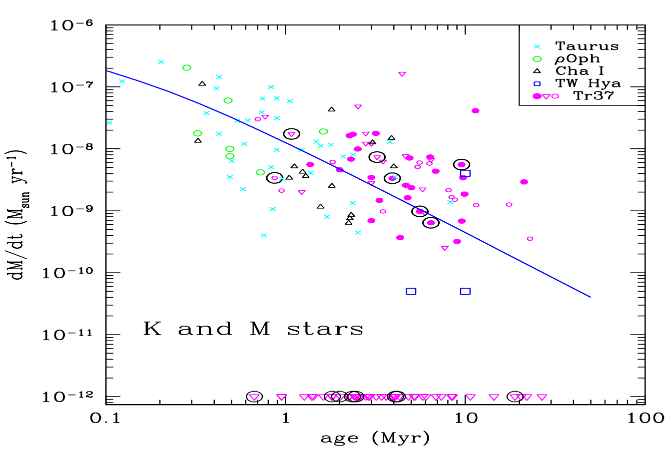

FIGURE 2. Accretion rates of K and M stars versus age in Tr 37, compared to the rates in other regions (Muzerolle et al. 2000, APJ 535, L47) and to a viscous disk evolutionary model (Hartmann et al. 1998, ApJ 495, 385). The transition objects (TO) with inner holes are marked with large circles.

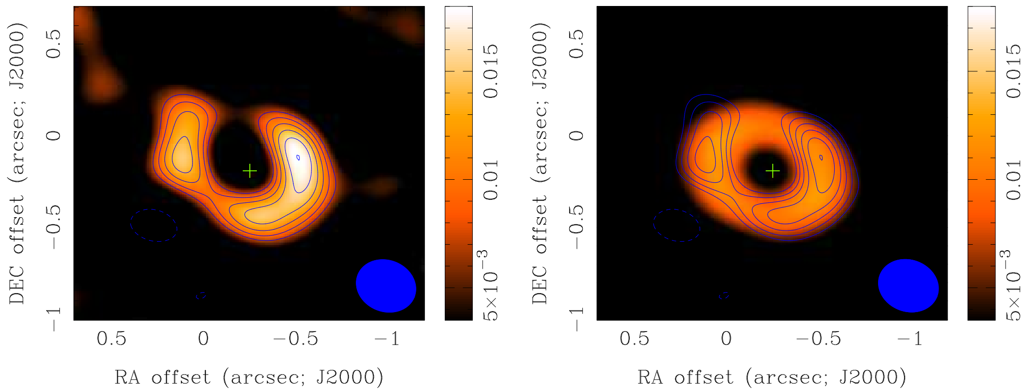

FIGURE 3. (a) SMA 340 GHz dust continuum image of LkHα 330 clearly showing an inner disk hole of approximately 40 AU radius. The $0\farcs28 \times 0\farcs33$ beam is plotted at the bottom right. (b) Model of LkHα 330 overlaid with contours from the data. The model, based on spectrophotometry, is in good agreement with the data lending confidence to current interpretations of SEDs with significant dust emission deficits in the inner regions.

lower than typical rates in Taurus. About 50% of the transition disks[1] in Tr 37 are accreting, and their accretion rates are low, but not special in comparison to other normal disks. They are typically higher than what is required for photoevaporation to become efficient. Observations in Taurus (Najita et al. 2007) reveal similar accretion rates for transitional disks, despite the age difference between both clusters and the differences in the accretion rates for normal disks, which may be an indication of common properties among transitional disks of different ages.

Figure 2 shows that accretion rates generally decrease with age, but there are large individual variations for stars with similar ages and spectral types. Finally, objects with no evidence of accretion ($\dot{M} < 10^{-12}\,M_\odot/yr$), having typically no disks or transition disks, are found at all ages. Read more in Sicilia-Aguilar et al. (2005, 2006a,b, 2008) .

3. *Childhood to Adolescence: Dust and Gas Clearing in Disks*

Joanna Brown discussed different observations of inner holes in protoplanetary disks. Mid-infrared spectrophotometry of protoplanetary disks have revealed a small sub-class of objects with spectral energy distributions (SEDs) that suggest the presence of large inner gaps with low dust content, often interpreted as a signature of young planets. New 340 GHz radio maps (see Fig. 3) confirm this hypothesis, showing direct evidence for the absence of dust opacity in the innermost 20-50 AU of LkHα 330, SR 21 and HD 135344, which is in excellent agreement with the predictions from SED modeling.

However, the SEDs are notoriously difficult to interpret as multiple physical scenarios can result in the same SED. An alternative explanation to the planet interaction hypothesis is that the “gaps” are simply a consequence of faster grain growth in the inner

[1] “Transition disks” are here considered as disks with inner opacity holes in the near IR.

regions, leading to an effective reduction of grain opacity (e. g. Dullemond & Dominik 2005). Alternatively, EUV radiation can ionize the gas at the surface of the inner disks, which makes it gravitationally unbound, creating true physical gaps by the action of winds as time progresses, even without planet interaction (Alexander et al. 2006a,b).

These different scenarios should be distinguishable by gas signatures. In fact, high resolution near IR spectra from Keck NIRSPEC and VLT CRIRES reveal that CO gas is present well inside these "dust gaps" (Pontoppidan et al. 2008), i. e. the gas distribution is different from the dust distribution. It is noteworthy that, in general, the gas distribution is different in different disks. See also Brown et al. (2007,2008).

4. Thermal and Chemical Models of Protoplanetary Disks

Inga Kamp summarized the present status of thermo-chemical disk models which help to understand the location and physical properties of the gas such as density, temperature, and composition. A number of 2D models of young protoplanetary disks (Kamp & Dullemond 2004, Jonkheid et al. 2004, Nomura & Millar 2005, Gorti & Hollenbach 2007) are pioneering in combining a complex chemical reaction network with a detailed description of the physics and thermal balance in the disk. These models reveal hot surface layers (see Fig. 1) where the gas lines are already optically thick whereas the dust is still optically thin.

Compared to PDRs, protoplanetary disks have strong vertical density gradients and the irradiation source, the central star, has a larger impact and a different energy distribution than the diffuse interstellar UV radiation field. Young stars often show strong X-rays either due to ongoing accretion of disk/envelope material onto the star or due to chromospheric activity. The presence of X-rays enhances the ionization fraction of the disk surface (Glassgold et al. 2004, Meijerink et al. 2008), raises molecular abundances due to efficient ion-molecule chemistry (e. g. HCN; Aikawa & Herbst 1999) and enhances line emission from molecular tracers such as H_2 (Nomura et al. 2007).

Future steps in the thermo-chemical disk modeling are a self-consistent computation of the vertical disk structure, the gas phase chemistry, and gas thermal balance. First results from Nomura & Millar (2005) and Gorti & Hollenbach (2007) contain compromises either for the determination of the dust temperature (two-layer approximation) or the size of the chemical network and number of heating/cooling processes. Also, the physical conditions in the inner few AU and the midplane resemble more stellar atmospheres than PDRs. Hence, a series of additional chemical reactions (three-body) and heating/cooling processes (molecular vibrational and ro-vibrational transitions, atomic electronic transitions, etc.) have to be added (see Fig. 4).

The fully self-consistent radiative transfer remains to-date the most challenging problem in the thermo-chemical disk models. Line radiation in the thermal balance is often approximated by an escape and pumping probability formalism. More accurately, the mean radiation field J_ν in the disk is determined by dust continuum and gas line opacity. Computing this mean radiation field thus requires another loop of iteration as the gas temperature depends on J_ν (line pumping) and the gas opacity depends on the gas composition and temperature.

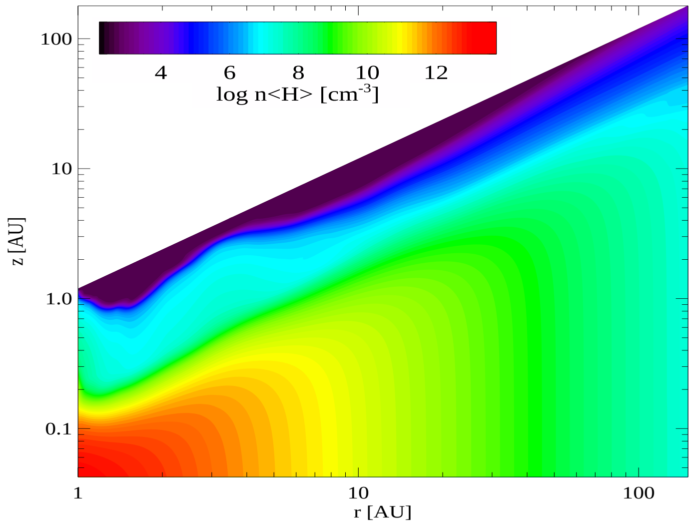

FIGURE 4. Density distribution $n_{\langle H \rangle}(r,z)$ in a TW Hya disk model with parameters $M_{\rm disk} = 10^{-3}$ M$_\odot$, $M_* = 0.6$ M$_\odot$, $L_* = 0.23$ L$_\odot$ and $T_{\rm eff} = 4000$ K. This model includes the solution of hydrostatic stratification within the iteration of gas chemistry and energy balance, and a full 2D dust continuum radiative transfer (ray-based method with accelerated Λ iteration, Woitke, Kamp & Thi in preparation). These self-consistent models do not only produce a "puffed-up" inner rim, but also a second less pronounced rim at $r \approx 3-4$ AU due to heating by absorption of stellar IR radiation in Fe II lines.

5. Different Organic Chemistry in Disks around Sun-like and Cool Stars

Ilaria Pascucci presented low-resolution SPITZER spectra ($\sim 7-14\mu$m) of 61 protoplanetary disks showing molecular emission bands. It is generally assumed that the organic compounds of the presolar nebula are representative to all protoplanetary disks, implying that planets around different stars will all have the same bulk composition. In a large dedicated effort with the Spitzer Space Telescope, Pascucci et al. (2009) show that the abundance of simple organic molecules like C_2H_2 and HCN differ in disks around cool stars from that in disks around sun-like stars (see Fig. 5). Because over 80% of stars in the galactic disk are cooler than the Sun, this study indicates that the circumstellar inventory of the Solar System may not be typical. HCN is likely to be a building block of more complex organic molecules like adenine. The sample also contains the first detections of organic molecules in the disks around brown dwarfs. See also Pascucci et al. (2006, 2007), Apai et al. (2005) and Luhman et al. (2007).

6. Gas Dispersal and Disk Evolution

Richard Alexander reviewed recent developments in the modelling of disk evolution and gas dispersal. In the "standard" hydrodynamical picture of disk evolution, the gas is subject to viscous transport of angular momentum and stellar photoevaporation (Alexander et al. 2006a,b). If the stellar EUV flux is sufficiently strong, it can ionize hydrogen, which produces high temperatures ($T \approx 10000$ K) and small mean molecular weights

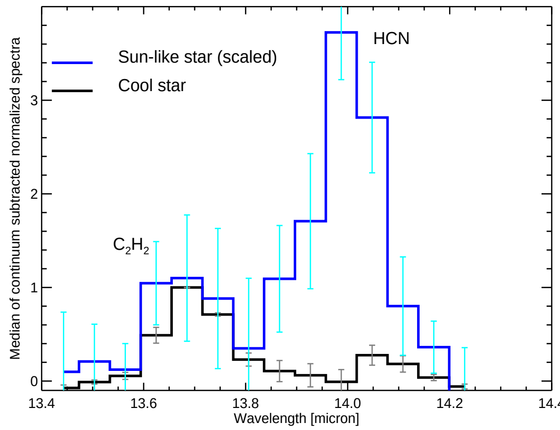

FIGURE 5. Median of continuum-subtracted and normalized spectra for the sun-like stars (blue) and cool stars (black) samples presenting C_2H_2 and/or HCN emission bands. The spectra are normalized to the peak of emission and scaled to match the C_2H_2 emission in the two samples. The error bars are the standard deviations of the normalized spectra. If cool stars had the same flux ratio of HCN versus C_2H_2 as the sun-like stars do, HCN emission would have been easily detected toward them.

$\bar{\mu}$ at the disk surface. Outside of some critical radius, the gas becomes thereby gravitationally unbound and a slow ($\approx 10\,\mathrm{km/s}$) photo-evaporative wind forms. The combination of photoevaporation and viscous evolution can form inner holes (see Fig. 1 in Alexander et al. 2006b) and finally clears out the disk inside-out on a relatively short timescale of about 10^5yrs. There are, however, a number of uncertainties in this picture, for example the proper determination of the stellar EUV and FUV flux as function of age and its attenuation by the accretion column. FUV photoevaporation models need sophisticated radiative transfer, which is difficult to couple to the hydrodynamics.

One key observation to test these models are the profiles of the [Ne II] 12.81μm emission line. This line has been detected by SPITZER towards around 20 T Tauri stars (Pascucci et al. 2007, Lahuis et al. 2007), and is thought to arise from the upper disk atmosphere (Herczeg et al. 2007). Recent line radiative transfer models based on photoevaporative winds (Alexander et al. 2008b) predict that the line is broad (30 – 40 km/s) and double-peaked when viewed edge-on, but narrower (≈ 10 km/s) and slightly blueshifted when viewed face-on. This blue-shift should be detectable with current echelle spectrographs on 8m-class telescopes, and Alexander suggested that the detection of such a blue-shift could provide the first direct test of photoevaporation models. See also review article by Alexander (2008a).

7. Gas in Debris Disks: Clues to the Late Stages of Planet Formation

Aki Roberge investigated the difficult case of gas in debris disks. These disks around nearby main sequence stars are composed of moderate amounts of small dust grains and gas generated by collisions between and evaporation of asteroids and comets. The gas component in debris disks has resisted observation for a long time and little is known

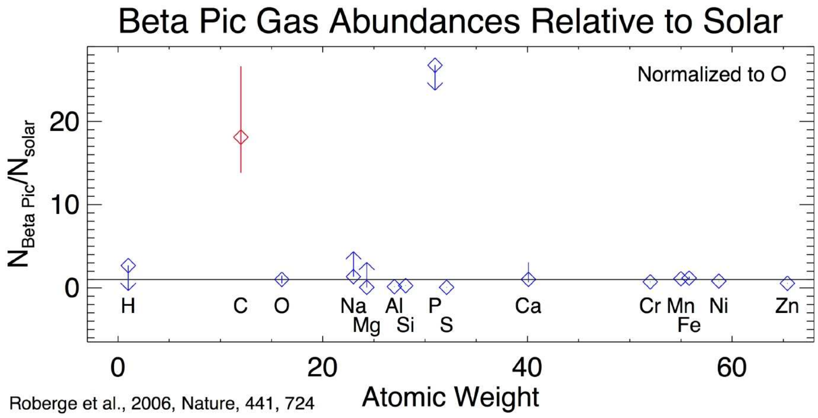

FIGURE 6. The bulk composition of the Beta Pictoris circumstellar gas. The midplane elemental abundances relative to solar abundances are plotted with diamonds. Upper and lower limits are indicated by arrows. The abundances are normalized to oxygen. Most measured elements have nearly solar abundances, as does the central star. The exception is carbon (red diamond), which is highly overabundant.

about its composition. Nonetheless, at least some debris disks contain gas that can be currently studied with UV/optical absorption spectroscopy if seen edge-on. Debris gas holds important clues to the composition of extrasolar planetesimals during the late stages of planet formation and the formation of terrestrial planet atmospheres. Figure 6 displays a highly unusual and interesting characteristic of the gas in the Beta Pic debris disk as compared to younger protoplanetary disks: an extreme carbon overabundance. Details may be found in Roberge et al. (2006) and Roberge & Weinberger (2008).

CONCLUSIONS

The gas component in protoplanetary disks can be observed by emission lines from the ultraviolet to millimeter. The structure, dynamics, temperature structure and chemical composition of the gas in the disks provide the initial for planet formation. The evolution of the gas component from massive gas-rich disks to almost gas-free debris disk, including the formation of central holes, limits the timescale for giant planet formation, and the delivery of water and organic material to terrestrial planets.

Spectroscopic measurements of gas in disks are generally more challenging than broadband observations of dust both in terms of observations and theory, but they provide complementary information on the disk structure, in addition to unique constraints on kinematics and chemistry. Future facilities, operating at near-infrared to millimeter wavelengths such as JWST, HERSCHEL, SOFIA, and ALMA, will open up this field and lead to dramatic advances in our understanding of disk evolution and planet formation.

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